Accretion-Ejection Instability and a "Magnetic Flood" scenario for GRS 1915+105

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Abstract. We present an instability, occurring in the inner region of magnetized accretion disks, which seems to be a good candidate to explain the low-frequency QPO observed in many X-ray binaries. We then briefly show how, in the remarkable case of the microquasar GRS 1915+105, identifying this QPO with our instability leads to a scenario for the $\sim$ 30 mn cycles of this source. In this scenario the cycles are controlled by the build-up of magnetic flux in the disk.

INTRODUCTION

This contribution comes from two different lines of work: the first one is purely theoretical, and has led us to present recently [1] an instability which may occur in the inner region of magnetized disks. We have called it Accretion-Ejection Instability (AEI), because one of its main characteristics is to extract energy and angular momentum from the disk, and to emit them *vertically* as Alfven waves propagating along magnetic field lines threading the disk. These Alfven waves then may deposit the energy and angular momentum in the corona above the disk, providing an efficient way to energize winds or jets from the accretion energy.

The second approach has consisted in the comparison of this instability with the observed properties of the low-frequency (.5 - 10 Hz) Quasi-Periodic Oscillation (QPO) observed in the low and hard state of the micro-quasar GRS 1915+105. The very large and fast growing number of observational results on this source gives access to many aspects of the physics of the disk. They allow

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this comparison to rely on basic properties of the instability, and on more detailed ones, such as the correlation between the QPO and the evolution of the disk and coronal emissions (identified respectively as multicolor black body and comptonized power-law tail in the X-ray spectrum).

This comparison encourages us to consider that the AEI may indeed be the source of the QPO. Thus we proceed by considering the ~ 30 mn cycles of GRS 1915+105. These cycles are the most spectacular in the gallery of behaviors and spectral states of this source, in particular because multi-wavelength observations have shown IR and radio outbursts coinciding with them, consistent with the synchrotron emission from an expanding cloud ejected at relativistic speeds. These cycles have been analyzed in great details, and the QPO shows a very characteristic and reproducible behavior. We have thus built a scenario, starting from the identification of the QPO with the AEI, and considering how this could explain the evolution of the source during the cycle. We refer to it as a *magnetic flood* scenario, because we are led to believe that the cycle is controlled by the build-up of the vertical magnetic flux stored within the disk. The scenario is compatible with the available information on this type of cycle, explains a number of results in existing data, and leads to intriguing considerations on the behavior of GRS 1915+105.

ACCRETION-EJECTION INSTABILITY

We will present the instability here only in general terms, and refer to our recent publication [1] for detailed derivation and results. It appears in disks threaded by a vertical magnetic field, of the order of equipartition with the gas pressure ($\beta = 8\pi p/B^2 \lesssim 1$). The instability appears essentially as a spiral density wave in the disk, very similar to the galactic ones, but driven by the long-range action of magnetic stresses rather than self-gravity. The main difference lies in the amplification mechanism: instability results from the coupling of the spiral density wave with a *Rossby wave*. Rossby waves, associated with a gradient of vorticity, are best known in planetary atmospheres, including the other GRS – the Great Red Spot of Jupiter. In the present case differential rotation allows the spiral wave to grow by extracting energy and angular momentum from the disk, and transferring them to a Rossby vortex at its corotation radius. This radius is constrained by the physics of the spiral to be a few times ($\sim 2-5$ for the azimuthal wavenumber $m = 1$, *i.e.* a one-armed spiral) the inner radius of the disk.

A third type of wave completes the description of the instability: it is an Alfven wave, emitted along the magnetic field lines towards a low-density corona above the disk. The mechanism here is simply that the Rossby vortex twists the footpoints of the field lines in the disk. This twist will then

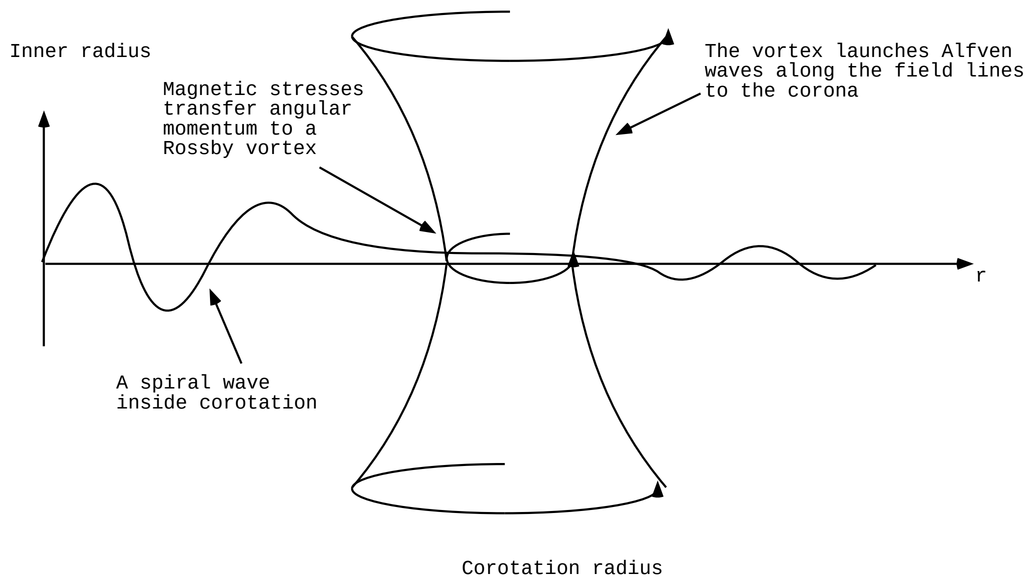

FIGURE 1. The propagation of the wave in the disk and its corona. A spiral wave grows by extracting energy and angular momentum from the disk, and transferring them to a Rossby vortex. The latter in turn transfers them to an Alfven wave toward the corona.

propagate upward, carrying to the corona the energy and angular momentum extracted from the disk by the spiral.

The mechanism is thus quite complex; this comes essentially from differential rotation, which allows a mixing of waves which would otherwise evolve independently. It results in an instability, growing on a time scale of the order of r/h times the rotation time (where h is the disk thickness and r its radius). We will present here its main characteristics, which will be essential in what follows:

• It occurs when the vertical magnetic field B_0 is near equipartition ($\beta \lesssim 1$) and presents a moderate or strong radial gradient.

• The efficiency of the coupling to the Rossby wave selects modes with low azimuthal wavenumbers (the number of arms of the spiral), $m = 2$ or $m = 1$ usually, depending on a number of parameters (density and temperature profiles, field strength, etc.)

• For a given m, the mode frequency is close to $\omega \approx (m-1)\Omega_{int}$, the rotation frequency at the inner disk radius. In the special case of the $m = 1$ mode, the frequency is usually of the order of $\sim .2 - .5$ times Ω_{int}.

• By analogy with galactic spirals, we can expect that these properties result in the formation of a large scale, quasi-stationary spiral structure rather than in a turbulent cascade to small scales.

• This should strongly affect the structure of the disk. Indeed, underlying the usual model of turbulent viscous transport in a disk (leading to Shakura and Sunyaev's model of α disks) is the assumption of small scale turbulence. This leads to a *local* deposition of the accretion energy, efficiently heating the disk. Here on the other hand, the accretion energy is transported away by *waves*: extracted from the disk by the spiral wave, it is first transferred to the Rossby vortex, then to Alfven waves. Thus, here as in galaxies, the connection between gas accretion and disk heating is not as straightforward as in α-disks.

MAGNETIC FLOOD SCENARIO

The low-frequency QPO in GRS 1915+105 has been the object of many recent studies [2,3]. During the $\sim$ 30 mn cycles of this source, the QPO appears only during the low state, and its frequency varies in a repetitive manner during that phase. Let us convert its frequency ν_{QPO} to a keplerian radius r_{QPO}, and compare it to the color radius r_{color} resulting from a multi-color black body model of the disk emission: observations show that the ratio r_{QPO}/r_{color} remains of the order of 5 while both radii vary during the low state. It is usually considered that r_{color} gives a measure of the internal radius r_{int} of the disk, although the ratio r_{color}/r_{int} is subject to some uncertainties. It is thus very tempting to consider that the QPO originates from a pattern in the disk, rotating at a frequency corresponding to a radius r_{QPO} of the order of a few times r_{int}. This may be supported by a correlation, found between ν_{QPO} and a higher frequency feature in various binary systems, including neutron star and black hole binaries [4]. Although the evidence is fragile in the case of GRS 1915+105, it would lead to consider that the ratio r_{QPO}/r_{int} is of the order of 5, in agreement with the previous result, and corresponding to the value we expect for the $m = 1$ AEI. This, and more detailed arguments to be presented elsewhere, leads us to tentatively identify the AEI as the source of the QPO, and to consider how this could fit with the 30 mn cycles of this source.

We start from the conditions responsible for the onset of the instability, *i.e.* a change in B_0 or its radial gradient. We find better agreement with the former, and in this case the sudden transition from the "high and soft" state to the "low and hard" one would find a natural explanation: one has to remember that the best candidate to explain accretion in a magnetized disk is the magneto-rotational instability (MRI) [6]. It appears in disks with low magnetization ($\beta > 1$), and results in small-scale turbulence which causes viscous accretion, in agreement with a standard α disk.

Let us consider that in the high state the disk extends down to its last stable orbit at r_{LSO}, as suggested by the consistent minimal value of r_{color}, and that accretion is caused by the MRI, following an α prescription. The MRI might be responsible for the "band-limited noise" observed in power density spectra (below the QPO frequency, *i.e.* farther in the disk, when the QPO is present). Although numerical simulations of the MRI give estimates of the resulting α, *i.e.* turbulent viscosity, they are not able at this stage to give the associated turbulent magnetic diffusivity, so that the evolution of the magnetic flux in the disk cannot be prescribed. Our main assumption is that in these conditions vertical magnetic flux builds up in the disk: either because it is dragged in with gas flowing from the companion, or from a dynamo effect [5]. This is actually the configuration observed near the center of the Galaxy.

Then the field must grow in the disk, so that β decreases until it reaches $\beta \simeq 1$, at which point the MRI stops and our instability sets in, appearing as the low-frequency QPO. The most important consequence is that turbulent disk heating stops, so that the disk temperature should drop, further reducing β. The abrupt transition from the high to the low state thus finds a natural explanation, as a sharp transition between a low magnetization, turbulently heated state to a high magnetization one, where disk heating stops and accretion energy is redirected toward the corona (although estimating what fraction of this energy is actually deposited in the corona depends on the physics of Alfven wave damping).

The content of the space between the disk (when it does not extend down to r_{LSO}) and the black hole is not known. It might be an ADAF, or a large-scale, force-free magnetic configuration holding the magnetic flux frozen in the black hole (following the Blandford-Znajek mechanism). In both cases the condition which determines the inner disk radius r_{int} must be complex, but it is reasonable to assume that a drop in the disk pressure could explain the increase of r_{color} at the onset of the low state. Continuing accretion from the outer disk region would then move the disk back toward the last stable orbit, as seen during the low state.

The light curves show an "intermediate spike", halfway through the low state. At this time r_{color} is back to its minimal value, the QPO stops, and the coronal emission decreases sharply. This is also when the infra-red synchrotron emission, presumably from a "blob" ejected at relativistic speed, begins [7]. It is then natural to consider that at this time a large-scale magnetic event, possibly reconnection with the magnetic flux surrounding the black hole, causes ejection of the coronal plasma. This allows the disk to return to a lower magnetization state, so that once it has fully recovered it can start a new cycle in the high and soft state.

CONCLUSION

The properties of the low-frequency QPO in GRS 1915+105 have led us to tentatively identify it with the Accretion-Ejection Instability. This has allowed us to build up a scenario for the 30 mn cycles of this source. In contrast with global descriptions, such as α disks, this does not allow us to predict specific spectral signatures: in the same manner, knowledge of Rossby waves would hardly allow one to predict the existence and appearance of the Great Red Spot on Jupiter. On the other hand, the scenario is qualitatively compatible with all the information we have about these cycles. It explains why and how the QPO appears, how its frequency varies with the color radius, and why the transition from the high to the low state has to be a sharp one. Future work will be devoted to the QPO behavior at other times in GRS 1915+105, and then to other sources (black hole or neutron star binaries) where the identification of the QPO might give access to additional physics.

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